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Geothermal Electricity Technologies Evaluation Model

DOE Tool for Assessing Impact of Research on Cost of Power

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GEOTHERMAL ELECTRICITY TECHNOLOGIES EVALUATION MODEL DOE TOOL FOR ASSESSING IMPACT OF RESEARCH ON COST OF POWER

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ABSTRACT

The U.S. Department of Energy (DOE) has developed a spreadsheet model to provide insight as to how its research activities can impact of cost of producing power from geothermal energy. This model is referred to as GETEM, which stands for "Geothermal Electricity Technologies Evaluation Model". Based on user input, the model develops estimates of costs associated with exploration, well field development, and power plant construction that are used along with estimated operating costs to provide a predicted power generation cost. The model allows the user to evaluate how reductions in cost, or increases in performance or productivity will impact the predicted power generation cost. This feature provides a means of determining how specific technology improvements can impact generation costs, and as such assists DOE in both prioritizing research areas and identifying where research is needed.

BACKGROUND

Since the inception of the DOE Geothermal Program over 30 years ago, a wide gamut of research activities have been conducted in pursuit of expanding the use of geothermal energy in meeting the nation's demand for electrical power. Quantifying how specific research will increase the power generated is difficult, and is made more so by the variation in technology needs for different geothermal resources. The basic approach utilized in evaluating technologies has used engineering economics to identify those having the greatest promise of increasing the total power generation (largely by reducing power generation costs).

Various approaches have been used to illustrate the economic benefit of technologies. Early power plant researchers used a "value analysis" that estimated the incremental impact of a technology on the power generation cost. Later, the economic model IMGEO was developed that predicted power generation costs, with added emphasis on predicting well costs.

More recently the GETEM model was developed, in part to allow the DOE Geothermal Program to conform to GPRA (Government Progress and Results Act) requirements for annual assessment and reporting of improvements in geothermal electric systems (Entingh and Mines, 2006). Both costs and performance are characterized in the model for currently available technologies, and then used to estimate Levelized Costs of Electricity (LCOE). GETEM allows the user to then assess how technology improvements will affect the LCOE. Defined base cases provide consistent reference conditions for assessing the relative benefits of different technology advances.

The GETEM model was developed by a team that included DOE, national laboratory, and industry personnel, with the lead role in the development shared by Dan Entingh from PERI and Gerry Nix from the National Renewable Energy Laboratory (NREL). Model development was based on being able to provide a representative estimate of the LCOE with minimal user input. This was, and remains a critical issue with the model:

- If user input is too arduous, the model will not be used by those for whom it was intended.
- Without sufficient detail, it is fortuitous if LCOE predictions are representative of current commercial power generation costs.

The initial model development was completed in 2006, though modifications continue. Recent efforts have attempted to address some of the shortcomings that were identified, and to make the model more robust.

MODEL DESCRIPTION

Estimates for the LCOE are derived using information provided by the user, and cost and performance correlations embedded in the model. User information is provided primarily in worksheets for either the binary plant (***BI-Input***), or the flash-steam plant (***FL-Input***). The user first provides information needed to define the base case LCOE.

For a project using a binary power plant, this requires up to 35 inputs; the flash plant requires up to 42 inputs. While this may seem like an ominous amount of information, most of these inputs need not be changed once this base case condition is defined. Once it is defined, the user can predict the impact of a technology improvement on the base case LCOE by modifying those inputs that are impacted by the technology. This is accomplished by inputting a change for a given parameter. The model multiplies that change by the calculated or inputted base case parameter to reflect how the user believes the technology impacts the cost and or performance of the plant, wells, etc.. As an example, if the user believes that technology advances will reduce the cost of drilling a well by 20%, a change of 0.80 is inputted as a change to well cost to reflect this decrease. If the model has calculated a drilling cost of $1,000,000 for the base case, the revised well cost for the "improved" plant will be $800,000. The binary project allows up to 40 changes to be made to reflect technology improvements; the flash plant allows up to 47 changes to be made.

Again, the user only indicates the fraction change in a given cost, performance, or other parameter used to calculate the LCOE. As these changes are made, the model displays the updated LCOE for improved plant at the top of the input worksheet, along with the base case LCOE. The model also indicates parameter values being used in both scenarios for the LCOE calculations.

The model's output sheets for both the binary (***BI-Output***) and flash (***FL-Output***) systems provide summaries of the plant output, well field size, and both capital and operating costs calculated by the model. This information is also summarized on the ***Summary*** worksheet, though with less detail.

The calculations in the model are based on user defined resource temperature, plant size, well costs, well depth, and well flow rate. Based on the resource temperature, the model calculates a plant performance (net plant output per unit geothermal fluid flow). The user can either use this value or input a value for plant performance. The total required flow rate is then determined using the defined net plant output and either the calculated or inputted plant performance.

Individual well costs are determined using the well depth and a user selected well cost curve (3 curves are incorporated in the model). The number of wells required are defined using the flow rate per well and the total flow required to produce the desired net plant output.

Capital costs associated with exploration activities are based upon inputted information for both exploration and confirmation success (ratio of successful wells to wells drilled). The number of exploration wells is also a function of the user provided input as to the size of the reservoir (defined by the amount of potential power found).

The power plant cost is determined as a function of both the resource temperature and the size of the power plant (net).

The LCOE contribution of the projected capital costs associated with the exploration and confirmation activities, well field drilling and the power plant are determined using the user defined utilization factor and fixed charge rate. For its calculations, DOE utilizes a fixed charge rate of 0.128.

The model also predicts Operating and Maintenance (O&M) costs that are based upon the type of power plant, the plant size, the type of downhole pump, and user provided information regarding maintenance costs (fraction of total capital cost). Royalty costs are also calculated as 10% of the annual field related costs; this approximates a Bureau of Land Management calculation. The user can change a number of the parameters used in calculating the O&M costs, however several of these changes must be made on the ***O&M*** and ***System*** worksheets; they are not changed from the plant's ***–Input*** worksheet.

Calculated costs are combined to generate a LCOE for both the base and improved system scenarios and exported to the various output worksheets.

BASIS FOR COST PREDICTIONS

One of the objectives in GETEM's development is that one be able to reference the basis for the projected LCOE's. Ideally GETEM's capital and operating cost predictions for a geothermal system would be based upon actual data. Unfortunately, the amount of actual data that is publically available is limited, and when available, frequently lacks sufficient detail to adequately characterize the system cost and performance. This is particularly true of the energy conversion systems, where the information available is typically the product of an engineering study, and not the cost or performance of an actual plant.

The development of the power plant performance and cost correlations were based upon selected prior studies. Binary power plant performance was based upon prior work at the Idaho National Laboratory that supported work done by Pritchett (1998). This work was used to develop a simple correlation that predicted the net power produced by the plant per unit mass flow of geothermal fluid, as a function of the resource temperature. The flash steam plant performance uses a similar correlation of performance as a function of temperature. The flash correlation was based upon the results from models developed for both single and dual flash-steam plants. The binary plant projections were based upon the assumed use of air-cooled condensers, while the flash-steam projections assumed the use of evaporative heat rejection systems. The projections of plant performance using these correlations were found to compare favorably with to plant performances reported in the 1995 EPRI Next Generation Geothermal Power Plant (NGGPP) study (Brugman, et al., 1995).

The cost correlations developed for both the flash-steam and binary power plants were derived using the plant costs reported in the NGGPP study. The cost correlations developed were for 50 MW,net plants as functions of the resource temperature. These costs were then scaled to the user's defined plant size using cost scaling factors derived from other work. Costs were escalated forward from 1995 to 2004 using a 1% escalation factor (team personnel were told in 2004 by a contributor to the NGGPP that the plant costs reported in that study were still representative of costs at that time.)

Three correlations were developed that predict wells costs as functions of the well depth. These correlations are representative of the range of costs that one might expect when drilling geothermal wells. They were developed by Sandia National Laboratory as part of an analysis of historical geothermal drilling costs. Work on this analysis was reported by Mansure, et al., (2005) at the Geothermal Resources Council 2005 Annual Meeting. The correlations developed from this data, and incorporated into GETEM reflect well costs in the year 2004.

The GETEM calculations for O&M costs are based largely on the experiences and observations of members of the GETEM team.

EXAMPLES OF MODEL PROJECTIONS

An example of GETEM's projections of the effect of a technology improvement that reduces drilling costs is shown in Figure 1. In this figure the effect of changing wells cost on the LCOE is shown for two different scenarios. In both scenarios, the resource temperature is 175°C, the well depth is 4,920 ft (1.5 km) and the base cases are defined using the GETEM correlation producing the highest well cost as a function of depth. The flash-steam system produces 50 MW, using production wells having artesian flow. The binary system produces 15 MW, and uses downhole pumps to increase fluid production. The predicted LCOE's for the base cases shown in the figure are 4.53 ¢/kW-h for the flash system and 6.69 ¢/kW-h for the binary system.

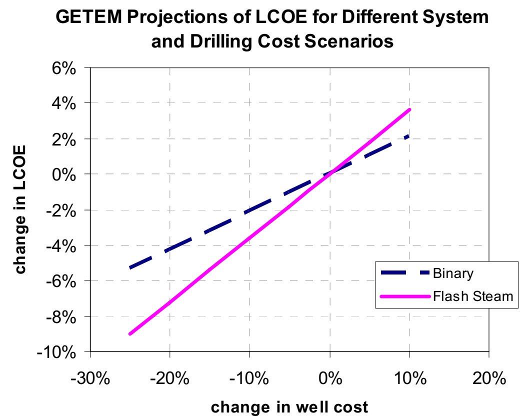

Figure 1. Example of GETEM projections for technology that reduces drilling costs

The results indicate that this technology improvement has a larger impact on the flash-steam system. This is because its well field and exploration costs are larger contributors to the LCOE than they were in the scenario used for the binary system. They are larger in the flash-steam system scenario in part because the binary conversion system costs are higher, but also because the binary conversion system is more efficient and utilized downhole pumps wells to increase well production, i.e., fewer wells per MW.

This example is not meant to suggest that drilling improvements are more important to reducing the LCOE for flash systems. Rather it is to illustrate that technology improvements that reduce well field development costs will have a greater impact on projects where those costs are relatively higher. Using the same analogy, technologies that reduce power plant costs will have the greatest benefit for those scenarios where the contribution of the energy conversion to the LCOE is greatest. In contrast, technologies that increase plant performance will have a greater impact when the well field development costs are a larger contributor to the LCOE.

LIMITATIONS

While the GETEM model provides the desired projections of the LCOE with relatively minimal user input, a good deal of caution must be used in assessing those results.

One of the premises in developing the cost and performance projections for GETEM was that NGGPP power plant costs from 1995 were still representative of current costs. While this may have been true through about 2004, it is doubtful that it is so today. Steel costs have risen significantly in recent years, and given that geothermal power plants and their piping systems are typically predominately made from steel, plant costs have likely increased.

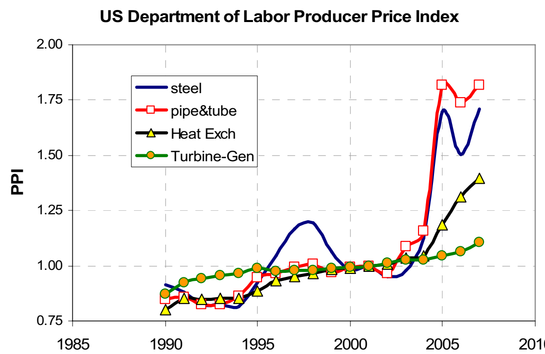

Figure 2. Producer Price Index for Steel and Conversion System Components

The Producer Price Index (PPI) reported by the U.S. Department of Labor for steel, piping, heat exchangers, and turbine-generators are shown in Figure 2. These PPI's indicate that costs did remain relatively constant from 1995 through about 2003, after which they began to rise. The PPI for piping and tubing essentially mirrors that of steel, indicating the labor contribution to fabricating the pipe is small compared to the cost of materials. In contrast, the PPI for the turbine-generator is the least affected by the rising steel costs; this is likely due to its fabrication being more labor intensive, with material costs being relatively small. While the GETEM team recognized that steel costs were changing, it postulated that at some future point these costs would return to historic norms. Though this is likely true, the model is deficient in predicting current costs if unable to accommodate the effects of the impact of higher steel costs.

In addition to the impact of higher steel costs on the capital cost projections, there were other issues with the cost and performance projections for the energy conversion systems.

- GETEM projections of conversion system cost and performance are functions of resource temperature only. There is also a functional relationship between the conversion system cost and performance. Plants that are designed to more efficiently convert the energy in the geothermal fluid into power are likely more expensive ($/kW). Generally more efficient (and expensive) plants are used with resources having higher well field development costs. Systems with resources that are inexpensive to develop are more apt to use conversion systems that are less efficient and consequently less expensive.
- GETEM conversion system costs projections are based upon the NGGPP costs for 50 MW plants and for resources with temperatures down to ~130°C. Extrapolation to lower resource temperatures and smaller plant sizes increases the uncertainty regarding the reasonableness of the cost estimates.
- The GETEM model did not easily facilitate examining technology improvements that targeted specific conversion system components.

To address these particular limitations, work is in progress to improve GETEM's projections of conversion system cost and performance, including incorporation of the effect of changing material (steel) costs.

REVISED GETEM MODEL

The subsequent revision of the GETEM model initially focused on improving the correlations for predicting the cost and performance of air-cooled binary power plants. The basis for the emphasis on this conversion system was the high priority assigned in DOE's Multiyear Program Plan to reducing the cost of conversion systems for resources between 130° and 175°C. For the same reason, this system was emphasized during initial GETEM development.

To better characterize the binary conversion system, correlations between the plant's performance and its cost were developed. This effort was based upon prior work done using ICARUS Process Evaluator (IPE), a cost estimating software package. Cost data generated with IPE was used to develop correlations to predict the cost of major components in the binary plant (geothermal heat exchangers, air-cooled condenser, turbine-generator, and working fluid pumps). An example of the predicted equipment costs as a function of plant performance for a 125°C resource is shown in Figure 3.

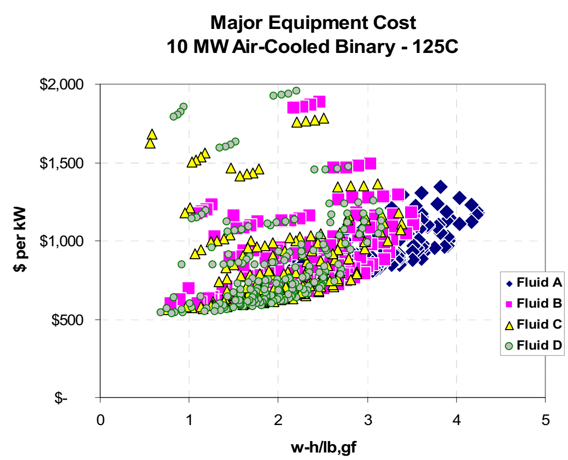

Figure 3. Binary conversion system equipment cost as function of plant performance

Similar equipment cost and performance data were derived at other resource temperatures between 100° and 200°C. The results at each temperature were similar to those shown in Figure 3; for each temperature, there was a minimum equipment cost associated with a given level of performance. The minimum cost conditions were extracted from the data set produced for each temperature, and used to derive correlations that predicted the sizes and cost of major components as functions of both plant performance and resource temperature.

This work was done for a nominal 10 MW,net plant. IPE component cost data was used to establish cost scaling factors with size, as well as to determine the contribution of both "materials" and "shop labor" to the fabrication cost of the equipment. The Department of Labor PPI's for steel and labor were then applied to both the materials and labor contributions, allowing equipment costs to be adjusted to the current year (or prior year). The IPE cost data for power plants was to develop installation multipliers to be applied to predicted equipment costs to establish the direct plant construction costs. In determining the total plant capital cost, indirect plant construction costs for engineering, permitting, home office expenses, etc., were defined as either a fixed cost or a percentage of the direct construction costs.

The revised cost correlations were used to predict both the component and plant costs of the binary plants defined in the NGGPP study. Both the equipment and total plant capital costs of the study's plants having temperatures between 125° and 200°C were predicted using the revised cost correlations. Those predictions were with ~6% of the costs reported in this study (the Producer Price Indices were used to adjust the predicted costs to 1995). This agreement gave credence to the results obtained with the revised cost correlations

A comparison was also made between GETEM's projection of the binary plant capital cost and the cost predicted using the revised cost correlations. That comparison is shown in Figure 4 for 15 MW plants.

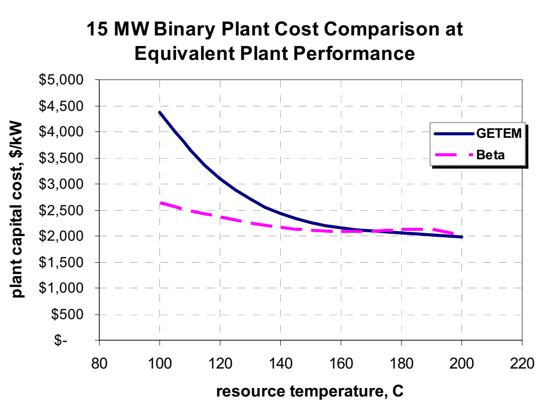

Figure 4. Cost comparison between GETEM and revised cost correlations

In this figure, the costs shown for the revised cost correlations (Beta) were determined at the GETEM predicted plant performance. The results indicate a good cost agreement for resource temperatures above ~150°C. At lower temperatures, there is significant deviation in the estimated costs. The comparison suggests that in developing the GETEM cost correlation, the NGGPP cost data was not correctly extrapolated to lower temperature resources and/or that the cost scaling factors with size were incorrectly assumed to be constant with resource temperature.

Because the revised correlations allow the plant cost to be related to its performance, an optimal plant performance can be approximated by minimizing the sum of the total plant capital cost, the exploration costs, and the well field construction costs, in terms of $/kW of power sold (plant output less geothermal pumping power). An example of this cost minimization is shown in Figure 5 for a 15 MW binary plant using a 150°C resource.

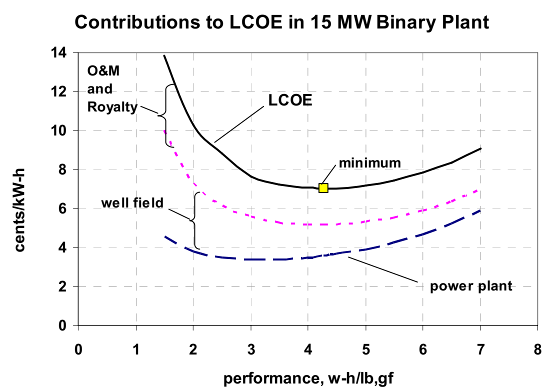

Figure 5. Effect of plant performance on LCOE for a 15 MW binary plant

The results in Figure 5 clearly illustrate the minimum in the LCOE that occurs as a function of plant performance. This minimum LCOE does not occur where the power plant capital costs are at a minimum, but rather near where the total project capital costs are minimized.

Different well field cost and resource temperature scenarios were evaluated to examine how the optimal plant performance compared to the values obtained with GETEM (where performance is a function of resource temperature only). Results indicated that the GETEM prediction agreed reasonably with the range of optimal performance obtained with a 150°C resource. As the resource temperature digressed from 150°C, there was increasing deviation between the GETEM prediction and the optimal performance determined with the revised correlations. In retrospect, this should have been expected, as the performance correlation in GETEM was based upon work prior work done for a 150°C resource. Heat exchanger and condenser pinch points used in predicting performance at all resource temperatures were fixed at values defined at 150°C. Recent work has indicated that optimal pinch points vary directly with resource temperature, i.e., lower resource temperatures generally have lower optimal pinch point temperatures. Plant performance varies indirectly with the pinch point; i.e., for the lower resource temperatures having lower optimal pinch points, the optimal plant performance would be higher. This is consistent with the comparison of the optimal performance projections at lower temperatures and the GETEM predicted performance.

Work has been started to improve GETEM's predictions of a flash-steam plant's cost and performance, though the revisions planned will not correlate cost to performance as has been done for the binary plant. The beta version of the next generation of GETEM that includes the revised binary and flash-steam plant correlations is expected to be completed by March, 2008.

One of the issues with GETEM that has not been addressed is how to best utilize the model to predict the cost of power produced from EGS systems. In theory the model can be used to predict those costs. At present, the model contains an input for Well Stimulation, which is applied to all production and injection wells. This feature could be utilized to characterize the cost of creating the subsurface heat exchange system. GETEM also includes input to reflect a decline in resource productivity with time, with the premise that an EGS resource may experience a more rapid decline in productivity. At this time it is anticipated that the EGS energy conversion system would be similar to that used for hydrothermal systems (and depicted in GETEM). The adequacy of the well cost correlations in GETEM to depict the cost of the deeper well that will likely be needed for EGS, will not be resolved until actual drilling data is obtained for these deeper wells. Any additional modifications to the model that will be needed to better facilitate LCOE predictions for EGS systems have not been identified.

MODEL AVAILABILITY

DOE is making the GETEM model available to the public, with the caveat that users recognize that the model has been developed to assist DOE in its analysis of its research program. The results that are produced are not "official" DOE estimates, nor should they be construed as representative of an actual plant. DOE asks that users of the model provide feedback to DOE indicating any issues or problems with the model's estimates. In particular DOE is requesting that any industry users provide feedback regarding the reasonableness of the estimates generated.

GETEM will be made available on DOE's web site http://www1.eere.energy.gov/geothermal/, along with its manual. Once the beta version of the next generation of GETEM is complete, it will also be available at this web site.

ACKNOWLEDGEMENT

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